SOLAR/1030-79/14

Solar Energy System Performance Evaluation

CHESTER WEST
SINGLE-FAMILY RESIDENCE
Huntsville, Alabama
September 1978 Through March 1979

U.S. Department of Energy

National Solar Heating and Cooling Demonstration Program

National Solar Data Program

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SOLAR ENERGY SYSTEM PERFORMANCE EVALUATION

CHESTER WEST
HUNTSVILLE, ALABAMA

SEPTEMBER 1978 THROUGH MARCH 1979

NORMAN M. LABBE, PRINCIPAL AUTHOR
JERRY T. SMOK, MANAGER OF RESIDENTIAL SOLAR ANALYSIS
LARRY J. MURPHY, IBM PROGRAM MANAGER

IBM CORPORATION
18100 FREDERICK PIKE
GAITHERSBURG, MARYLAND 20760

PREPARED FOR
THE DEPARTMENT OF ENERGY
OFFICE OF ASSISTANT SECRETARY FOR
CONSERVATION AND SOLAR APPLICATION
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H. JACKSON HALE, PROGRAM MANAGER

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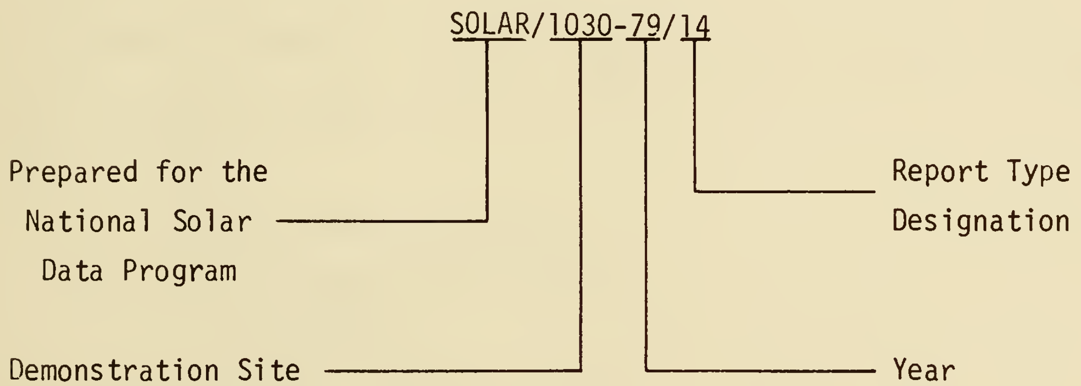
NATIONAL SOLAR DATA PROGRAM REPORTS

Reports prepared for the National Solar Data Program are numbered under specific format. For example, this report for the Chester West project site is designated as SOLAR/1030-79/14. The elements of this designation are explained in the following illustration.



o Demonstration Site Number:

Each project site has its own discrete number - 1000 through 1999 for residential sites and 2000 through 2999 for commercial sites.

o Report Type Designation:

This number identifies the type of report, e.g.,

- Monthly Performance Reports are designated by the numbers 01 (for January) through 12 (for December).

- Solar Energy System Performance Evaluations are designated by the number 14.

- Solar Project Descriptions are designated by the number 50.

- Solar Project Cost Reports are designated by the number 60.

These reports are disseminated through the U. S. Department of Energy Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

1. FOREWORD

The National Program for Solar Heating and Cooling is being conducted by the Department of Energy under the Solar Heating and Cooling Demonstration Act of 1974. The overall goal of this activity is to accelerate the establishment of a viable solar energy industry and to stimulate its growth to achieve a substantial reduction in nonrenewable energy resource consumption through widespread applications of solar heating and cooling technology.

Information gathered through the Demonstration Program is disseminated in a series of site-specific reports. These reports are issued as appropriate and may include such topics as:

- Solar Project Description
- Design/Construction Report
- Project Costs
- Maintenance and Reliability
- Operational Experience
- Monthly Performance
- System Performance Evaluation

The International Business Machines (IBM) Corporation is contributing to the overall goal of the Demonstration Act by monitoring, analyzing, and reporting the thermal performance of solar energy systems through analysis of measurements obtained by the National Solar Data Program.

The Solar Energy System Performance Evaluation Report is a product of the National Solar Data Program. Reports are issued periodically to document the results of analysis of specific solar energy system operational performance. This report includes system description, operational characteristics and capabilities, and an evaluation of actual versus expected performance. The Monthly Performance Report, which is the basis for the Solar Energy System Performance Evaluation Report, is published on a regular basis. Each parameter presented in these reports as characteristic of system performance represents over 8,000 discrete measurements obtained each month by the National Solar Data Network (NSDN). Documents referenced in this report are listed in Section 6, "References." Numbers shown in brackets refer to reference numbers in Section 6. All other documents issued by the National Solar Data Program for the Chester West solar energy system are listed in Section 7, "Bibliography."

This Solar Energy System Performance Evaluation Report presents the results of a thermal performance analysis of the Chester West solar energy system. The analysis covers operation of the system from September 1978 through March 1979. The Chester West solar energy system provides space heating and domestic hot water to a single-family dwelling located in Huntsville, Alabama. Section 2 presents a summary of the overall system results. A system description is contained in Section 3. Analysis of the system thermal performance was accomplished using a system energy balance technique described in Section 4. Section 5 presents a detailed assessment of the individual subsystems applicable to the site.

The measurement data for the reporting period was collected by the NSDN [1]. System performance data are provided through the NSDN via an IBM-developed Central Data Processing System (CDPS) [2]. The CDPS supports the collection and analysis of solar data acquired from instrumented systems located throughout the country. This data is processed daily and summarized into monthly performance reports. These monthly reports form a common basis for system evaluation and are the source of the performance data used in this report.

2. SUMMARY AND CONCLUSIONS

This section provides a summary of the performance of the solar energy system installed at Chester West, located in Huntsville, Alabama for the period September 1978 through March 1979. This solar energy system is designed to support the domestic hot water and space heating loads. A detailed description of Chester West solar energy system operation is presented in Section 3.

2.1 Performance Summary

The solar energy site was occupied from September 1978 through March 1979 and the solar energy system operated continuously during most of this reporting period. The periods of non-operation were as follows:

> November 1 until November 8. A safety switch activated causing collector draindown. The system was recharged with a new solution on November 8.
>
> The DHW subsystem was turned off from March 7 through March 26. DHW control maintenance on March 27 restored it to operation.

The total incident solar energy was 57.50 million Btu, of which 21.32 million Btu were collected by the solar energy system. Solar energy satisfied 74[(1)] percent of the DHW requirements and 15 percent of the space heating requirements. The space heating subsystem provided an electrical energy savings of 3.31 million Btu.

The overall weather conditions in Huntsville were very close to what was expected during the period covered by the report. The average ambient temperature of 52°F was exactly the same as the long-term average for the same period.

(1) Weighted average based on 3-month data: September, October, November (1978)

Heating and cooling degree-days of 3054 and 379 compared closely with long-term averages of 3125 and 347, respectively. Lastly, the site-measured average daily total incident solar energy on the collector array of 1201 Btu per square foot per day was about the same as the predicted 1224 Btu per square foot per day. However, there was quite a bit of variation when comparing measured and predicted heating degree-days and incident solar energy availability on a month-to-month basis. This fact is noted in the discussion of the space heating solar fraction which follows shortly.

The average efficiency of the collector array during the reporting period was 37 percent. This 37 percent is the ratio of collected energy to total energy incident on the array. The month-to-month efficiency ranged from a low of 24 percent in November to a high of 48 percent in December.

Average storage efficiency was based on September, October and November data. (See Section 2.2, for why the other months were excluded). There was an average storage efficiency of 53 percent. In the three months available, a trend toward an increase in efficiency from September to November was noted (29 percent, to 60 percent, to 88 percent). Heavier cold weather loads could account for this increased efficiency. It is quite likely the trend continued into the winter months and reversed itself as spring approached. This explanation is reinforced by the storage average temperatures. There was an overall storage average temperature of 123°F. Storage averaged 158°F in September, was down in the 80's and 90's in December through February, and had climbed to an average of 127°F in March. The installation of the new storage tank in March (see Section 2.2) would partially account for the rise in temperature in March.

The space heating solar fraction grew smaller as the outside ambient temperature became lower and the space heating load increased. The solar energy system was always supportive during the entire reporting period. The system experienced greater and greater difficulty in meeting the increasing winter space heating load demands using solar energy with a consequent rise in auxiliary thermal requirements. This is especially evident in January and

February, which had solar fractions of 6 percent and 10 percent, respectively. Over 65 percent of the space heating load over the 7-month reporting period occurred during these two months. Three factors can be offered as a partial explanation. More solar energy should have been available. Incident solar energy availability was much lower in January and February than in any other month of the 7-month period (see Table 5-1). In addition, both were substantially lower than the expected values. Consequently, solar energy collected values would unexpectedly be reduced during these months of high load. A second factor was the much higher than expected heating degree-days in January and February (see Table 5-1). The third factor was the condition of the original thermal storage tank, which was replaced in March (see Section 2.2). It is quite likely that unmeasured solar energy tank losses did occur, and at an increased rate as the weather grew colder.

2.2 Conclusions

Solar Energy System Controls. Less than optimum control settings allowed the DHW pumps to stay on longer than necessary during most of the reporting period. This condition was rectified late in March. The primary effect this condition exerted on the DHW subsystem was twofold: (1) the DHW operational energy requirements were slightly higher than required; and (2) a small amount of thermal energy was extracted from the DHW subsystem through the storage to DHW heat exchanger.

Thermal Storage Tank. A new galvanized steel tank, with external fiber glass insulation, was installed on March 1. The original fiberglass tank showed external signs of deterioration as reflected in observable water seepage. This condition naturally led to some thermal loss from storage.

Collector Loop. A safety switch was inadvertently activated on November 1, causing the collector solution to drain. The solar energy system was off from November 1 until November 8, at which time the collector loop was refilled with water. The loop was charged with the normal Solaryard G solution on November 9. Another drain-down occurred on November 19, at which time the loop was refilled with water. On November 20 the collector loop was refilled with an ethylene-glycol (32 percent)/water solution. This solution was replaced by a Solaryard G solution on March 2. At the same time, a backup battery powered system was installed.

The variety of fluids used in the collector loop provided different thermal transfer rates at different times. The backup battery power source greatly reduces the chances of a collector drain-down, when the normal power source fails.

Data Sensors. The two liquid flowmeters (one in the DHW loop and the other in the space heating loop) downstream from the thermal storage tank provided unreliable data from December through March. Debris from the original fiberglass tank and deposits attributed to the corrosive reaction of the liquid, and metals in these loops fouled the target area of both flowmeters.

Investigations are underway to select the best approach to clear the lines of debris and impede the corrosive reaction. In the interim, although the performance evaluation of the DHW and ECSS subsystems were limited, the evaluation of the space heating subsystem was unaffected. A complete evaluation of this latter subsystem was possible using flowrate data from the air side of the storage to space heating heat exchanger.

3. SYSTEM DESCRIPTION

The Chester West site is a single-family residence in Huntsville, Alabama. Solar energy is used for space heating the home and preheating domestic hot water (DHW). The solar energy system has an array of flat-plate collectors with a gross area of 225 square feet. The array faces south at an angle of 49 degrees to the horizontal. A glycerol-water solution is used as the medium for delivering solar energy from the collector array to storage; water is the medium for delivering solar energy from storage to the space heating and hot water loads. Solar energy is stored aboveground in a 500-gallon water storage tank. Auxiliary space heating is provided by an air-to-air heat pump and electrical heating elements which are designed to function in parallel with the solar energy space heating loop. Auxiliary hot water heating is provided in series with the solar energy DHW loop through the use of electrical heating elements in an 80-gallon DHW tank. The system, shown schematically in Figure 3-1, has three modes of solar operation.

Mode 1 - Collector-to-Storage: This mode activates when the control system senses a sufficient temperature difference between the collector and storage and remains active until the temperature difference drops below the accepted minimum. The collected energy is transferred to storage through a ring-type, liquid-to-liquid heat exchanger located in the storage tank. Pump P1 is operating.

Mode 2 - Storage-to-Space Heating: This mode activates when there is a demand for space heating. Solar energy is circulated to the conditioned space by solar-heated water from storage through a liquid-to-air heat exchanger located in the air-distribution duct. Pump P3 is operating.

Mode 3 - Storage-to-DHW Tank: This mode activates when the control system senses a sufficient temperature difference between storage and the DHW tank, and remains active as long as a sufficient temperature difference exists. Water circulates from the top of storage through a liquid-to-liquid heat exchanger located in the bottom of the DHW tank. Pump P2 is operating.

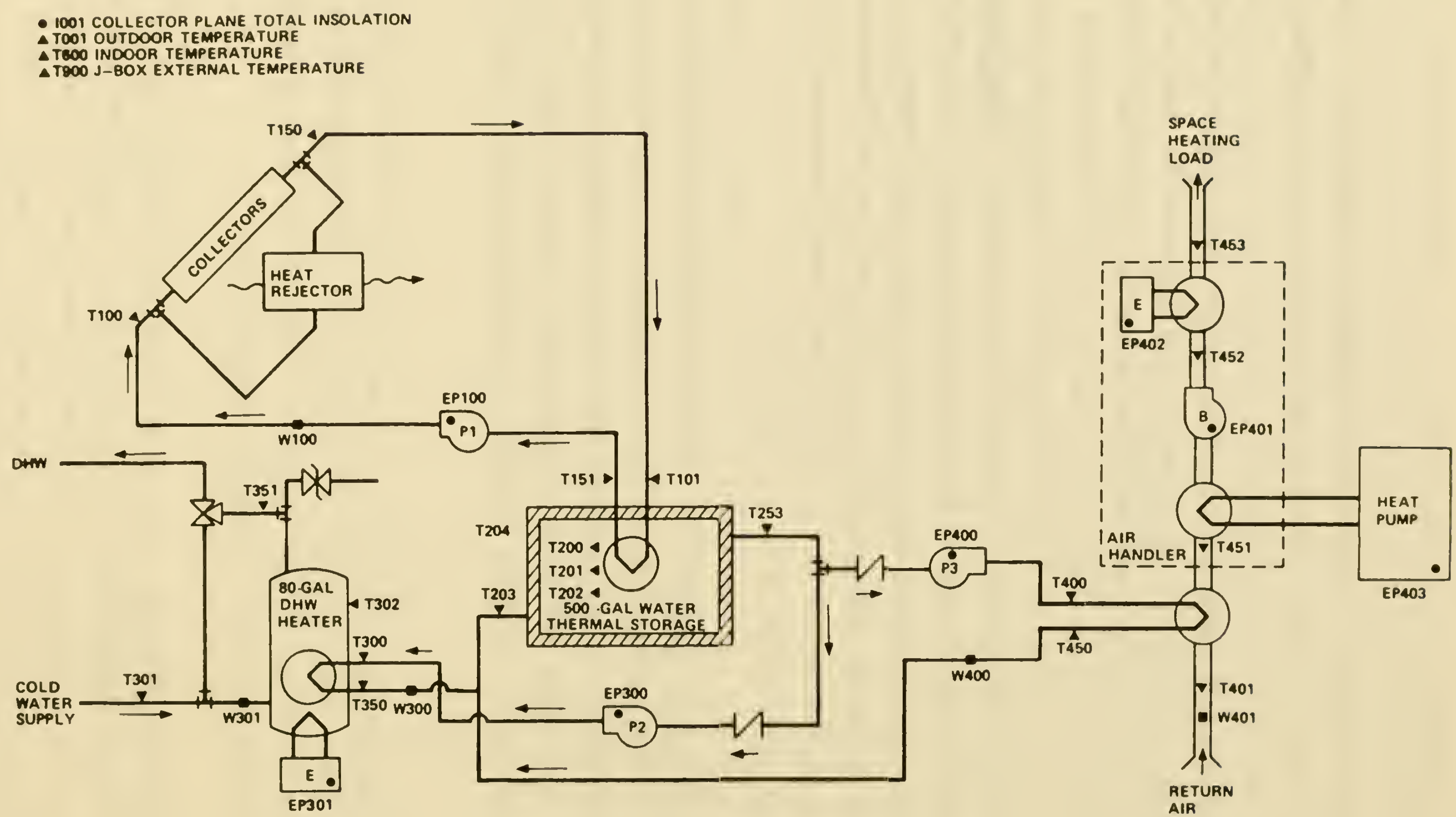


FIGURE 3-1. SOLAR ENERGY SYSTEM SCHEMATIC
CHESTER WEST

4. PERFORMANCE EVALUATION TECHNIQUES

The performance of the Chester West solar energy system is evaluated by calculating a set of primary performance factors which are based on those proposed in the intergovernmental agency report "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program" [3]. These performance factors quantify the thermal performance of the system by measuring the amount of energies that are being transferred between the components of the system. The performance of the system can then be evaluated based on the efficiency of the system in transferring these energies. All performance factors and their definitions are listed in Appendix A.

Data from monitoring instrumentation located at key points within the solar energy system are collected by the National Solar Data Network. This data is first formed into factors showing the hourly performance of each system component, either by summation or averaging techniques, as appropriate. The hourly factors then serve as a basis for calculating the daily and monthly performance of each component subsystem. The performance factor equations for this site are listed in Appendix B.

Each month, as appropriate, a summary of overall performance of the Chester West site and a detailed subsystem analysis are published. These monthly reports for the period covered by this Solar Energy System Performance Evaluation (September 1978 through March 1979) are available from the Technical Information Center, Oak Ridge, Tennessee 37830.

In the tables and figures in this report, an asterisk indicates that the value is not available for that month; N.A. indicates that the value is not applicable for this site.

5. PERFORMANCE ASSESSMENT

The performance of the Chester West solar energy system has been evaluated for the September 1978 through March 1979 time period. Two perspectives were taken in this assessment. The first views the overall system in which the total solar energy collected, the system load, the measured values for solar energy used, and system solar fraction are presented. Where applicable, the expected values for solar energy used and system solar fraction are also shown. The expected values have been derived from a modified f-chart analysis which uses measured weather and subsystem loads as input. The f-chart is a performance estimation technique used for designing solar heating systems. It was developed by the Solar Energy Laboratory, University of Wisconsin - Madison. The system mode used in the analysis is based on manufacturer's data and other known system parameters. In addition, the solar energy system coefficient of performance (COP) at both the system and subsystem level has been presented.

The second view presents a more in-depth look at the performance of individual subsystems. Details relating to the performance of the collector array and storage subsystems are presented first, followed by details pertaining to the space heating and domestic hot water (DHW) subsystems. Included in this section are all parameters pertinent to the operation of each individual subsystem.

In addition to the overall system and subsystem analysis, this report also describes the equivalent energy savings contributed by the solar energy system. The overall system and individual subsystem energy savings are presented in Section 5.5.

The performance assessment of any solar energy system is highly dependent on the prevailing weather conditions at the site during the period of performance. The original design of the system is generally based on the long-term averages for available insolation and temperature. Deviations from these long-term averages can significantly affect the performance of the system. Therefore, before beginning the discussion of actual system performance, a presentation of the measured and long-term averages for critical weather parameters has been provided.

5.1 Weather Conditions

Monthly values of the total solar energy incident in the plane of the collector array and the average outdoor temperature measured at the Chester West site during the reporting period are presented in Table 5-1. Also presented in Table 5-1 are the corresponding long-term average monthly values of the measured weather parameters. These data are taken from Reference Monthly Environmental Data for Systems in the National Solar Data Network [4]. A complete yearly listing of these values for the site is given in Appendix C.

During September 1978 through March 1979 the average daily total incident solar energy on the collector array was 1201 Btu per square foot per day. This was about the same as the estimated average daily solar radiation for this geographical area during the reporting period of 1224 Btu per square foot per day for a south-facing plane with a tilt of 49 degrees to the horizontal. The average ambient temperature during September 1978 through March 1979 was 52°F as compared with the long-term average of 52°F during the same period. The number of heating degree-days for the same period (based on a 65°F reference) was 3054, as compared with the summation of the long-term averages of 3125. The number of cooling degree-days for the same period (based on a 65°F reference) was 379, as compared with the summation of the long-term averages of 347.

Monthly values of heating and cooling degree-days are derived from daily values of ambient temperature. They are useful indications of the system heating and cooling loads. Heating degree-days and cooling degree-days are computed as the difference between daily average temperature and 65°F. For example, if a day's average temperature was 60°F, then five heating degree-days are accumulated. Similarly, if a day's average temperature was 80°F, then 15 cooling degree-days are accumulated. The total number of heating and cooling degree-days is summed monthly.

TABLE 5-1. WEATHER CONDITIONS
CHESTER WEST

MONTH	DAILY INCIDENT SOLAR ENERGY PER UNIT AREA[1] (Btu/Ft^2)		AMBIENT TEMPERATURE (°F)		HEATING DEGREE-DAYS		COOLING DEGREE-DAYS	
	MEASURED	LONG-TERM AVERAGE	MEASURED	LONG-TERM AVERAGE	MEASURED	LONG-TERM AVERAGE	MEASURED	LONG-TERM AVERAGE
SEP	1285	1481	76	73	0	11	330	248
OCT	1863	1504	60	62	181	159	22	72
NOV	1158	1178	57	50	260	441	9	0
DEC	1149	919	45	42	609	701	2	0
JAN	728	964	34	41	973	747	0	0
FEB	866	1177	40	44	701	605	0	6
MAR	1356	1347	54	51	330	461	16	21
TOTAL	X	X	X	X	3054	3125	379	347
AVERAGE	1201	1224	52	52	436	446	54	50

(1) In collector array plane and azimuth, unless otherwise indicated in Section 5.1.

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5.2 System Thermal Performance

The thermal performance of a solar energy system is a function of the total solar energy collected and applied to the system load. The total system load is the sum of the useful energy delivered to the loads (excluding losses in the system), both solar and auxiliary thermal energies. The portion of the total load provided by solar energy is defined as the solar fraction of the load.

The thermal performance of the Chester West solar energy system is presented in Table 5-2. This performance assessment is based on the 7-month period from September 1978 to March 1979. During the reporting period, a monthly average of 3.05 million Btu of solar energy was collected and the average system load was 4.90 million Btu. The average measured amount of solar energy delivered to the load subsystem was 1.48 million Btu or 0.22 million Btu less than the expected average value. The measured average system solar fraction was 61 percent as compared to an expected value of 77 percent. Note that the solar energy used and solar fraction values were based on averages which included only September, October and November 1978.

Figure 5-1 illustrates the flow of solar energy from the point of collection to the various points of consumption and loss for the reporting period. The numerical values account for the quantity of energy corresponding with the transport, operation, and function of each major element in the Chester West solar energy system for the total reporting period.

Solar energy distribution flowcharts for each month of the reporting period are presented in Appendix D.

Table 5-3 summarizes solar energy distribution and provides a percentage breakdown. Appendix E contains the monthly solar energy percentage distributions.

TABLE 5-2. SYSTEM THERMAL PERFORMANCE SUMMARY
CHESTER WEST

MONTH	SOLAR ENERGY COLLECTED (Million Btu)	SYSTEM LOAD (Million Btu)	SOLAR ENERGY USED (Million Btu)		SOLAR FRACTION (%)	
			EXPECTED	MEASURED	EXPECTED	MEASURED
SEP	3.46	0.23	0.8	0.75	100	88
OCT	4.27	0.68	1.9	1.97	98	91
NOV	1.85	2.81	2.4	1.71	70	51
DEC	3.80	*	*	*	*	*
JAN	1.99	13.50	*	*	*	*
FEB	2.21	8.95	*	*	*	*
MAR	3.74	3.23	*	*	*	*
TOTAL	21.32	29.4 (1)	5.1 (2)	4.43 (2)		
AVERAGE	3.05	4.90 (1)	1.7 (2)	1.48 (2)	77 (2)	61 (2)

* - Denotes unavailable data

(1) - Summation and average based on 6-month data: September, October, November 1978; January, February, March 1979.

(2) - Summation based on 3-month data: September, October, November 1978.

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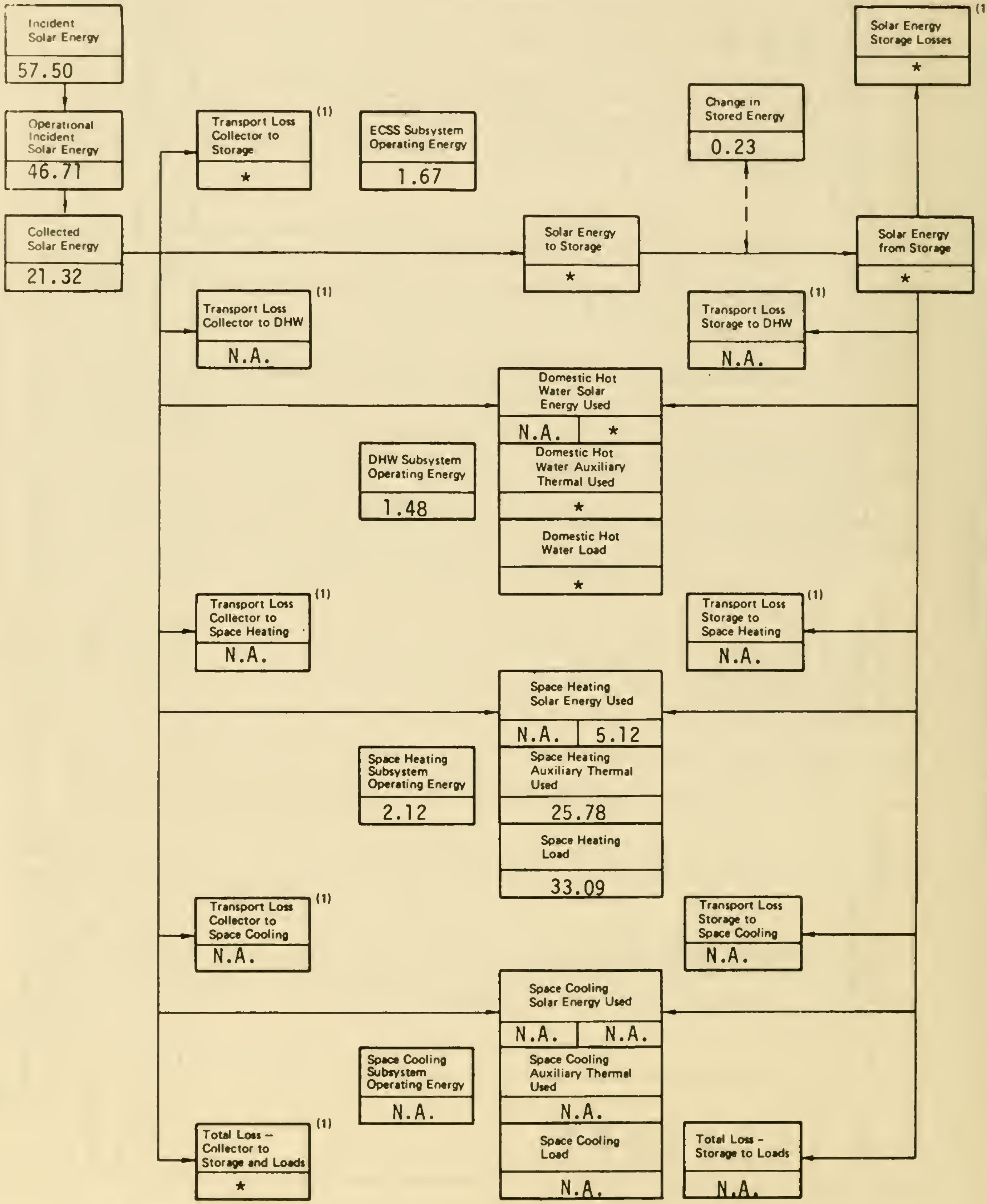
FIGURE 5-1. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - SUMMARY

CHESTER WEST



* Denotes Unavailable Data

N.A. denotes not applicable data

(1) May contribute to offset of space heating load (if known – see text for discussion)

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TABLE 5-3. SOLAR ENERGY DISTRIBUTION - SUMMARY - SEPTEMBER 1978 THROUGH MARCH 1979
CHESTER WEST

21.32	100%	million Btu	TOTAL SOLAR ENERGY COLLECTED
*	%	million Btu	SOLAR ENERGY TO LOADS
*	%	million Btu	SOLAR ENERGY TO DHW SUBSYSTEM
5.12	24 %	million Btu	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	%	million Btu	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
*	%	million Btu	SOLAR ENERGY LOSSES
*	%	million Btu	SOLAR ENERGY LOSS FROM STORAGE
*	%	million Btu	SOLAR ENERGY LOSS IN TRANSPORT
*	%	million Btu	COLLECTOR TO STORAGE LOSS
N.A.	%	million Btu	COLLECTOR TO LOAD LOSS
N.A.	%	million Btu	COLLECTOR TO DHW LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE HEATING LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE COOLING LOSS
N.A.	%	million Btu	STORAGE TO LOAD LOSS
N.A.	%	million Btu	STORAGE TO DHW LOSS
N.A.	%	million Btu	STORAGE TO SPACE HEATING LOSS
N.A.	%	million Btu	STORAGE TO SPACE COOLING LOSS
(±) .23	1 %	million Btu	SOLAR ENERGY STORAGE CHANGE (GAINS OR LOSSES)

* - Denotes unavailable data

N.A. - Denotes not applicable data

The solar energy coefficient of performance (COP) is indicated in Table 5-4. The COP simply provides a numerical value for the relationship of solar energy collected or transported or used and the energy required to perform the transition. The greater the COP value, the more efficient the subsystem. The solar energy system at Chester West functioned at a weighted average COP value of 2.65 for the reporting period September 1978 through November 1978. System COPs were not computable for December through March.

5.3 Subsystem Performance

The Chester West solar energy installation may be divided into three subsystems:

1. Collector Array and Storage
2. Domestic Hot Water (DHW)
3. Space Heating

Each subsystem is evaluated and analyzed by the techniques defined in Section 4 in order to produce the monthly performance reports. This section presents the results of integrating the monthly data available on the three subsystems for the period September 1978 through March 1979.

5.3.1 Collector Array and Storage Subsystem

5.3.1.1 Collector Array

Collector array performance for the Chester West site is presented in Table 5-5. The total incident solar radiation on the collector array for the period September 1978 through March 1979 was 57.50 million Btu. During the period the collector loop was operating the total insolation amounted to 46.71 million Btu. The total collected solar energy for the period was 21.32 million Btu, resulting in a collector array efficiency of 37 percent, based on total incident insolation. The average monthly solar energy delivered from the collector array to storage was 2.58 million Btu. Operating energy required by the collector loop was 1.67 million Btu.

TABLE 5-4. SOLAR ENERGY SYSTEM COEFFICIENT OF PERFORMANCE
CHESTER WEST

MONTH	SOLAR ENERGY SYSTEM COP	COLLECTOR ARRAY SUBSYSTEM SOLAR COP	DOMESTIC HOT WATER SUBSYSTEM SOLAR COP	SPACE HEATING SUBSYSTEM SOLAR COP	SPACE COOLING SUBSYSTEM SOLAR COP
SEP	1.25	12.81	2.27	0.0	N.A.
OCT	2.70	13.34	3.88	39.00	N.A.
NOV	5.03	13.21	2.83	60.00	N.A.
DEC	*	17.27	*	19.50	N.A.
JAN	*	12.44	*	25.67	N.A.
FEB	*	13.81	*	28.67	N.A.
MAR	*	9.35	*	36.5	N.A.
WEIGHTED AVERAGE	2.65	12.77	3.10(1)	30.12	N.A.

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* - Denotes unavailable data
N.A. - Denotes not applicable data
(1) - Weighted average based on 3-month data: September, October, November 1978

TABLE 5-5. COLLECTOR ARRAY PERFORMANCE
CHESTER WEST

MONTH	INCIDENT SOLAR ENERGY (Million Btu)	COLLECTED SOLAR ENERGY (Million Btu)	COLLECTOR ARRAY EFFICIENCY (%)	OPERATIONAL INCIDENT ENERGY (Million Btu)	OPERATIONAL COLLECTOR ARRAY EFFICIENCY (%)
SEP	8.68	3.46	40	7.46	46
OCT	12.99	4.27	33	11.37	38
NOV	7.82	1.85	24	4.18	44
DEC	8.01	3.80	48	7.15	53
JAN	5.08	1.99	39	4.01	50
FEB	5.46	2.21	41	4.37	51
MAR	9.46	3.74	40	8.17	46
TOTAL	57.50	21.32		46.71	
AVERAGE	8.21	3.05	37	6.67	46

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Collector array efficiency has been computed from two bases. The first assumes that the efficiency is based upon all available solar energy. This approach makes the operation of the control system part of array efficiency. For example, energy may be available at the collector, but the collector fluid temperature is below the control minimum; therefore, the energy is not collected. In this approach, collector array performance is described by comparing the collected solar energy to the incident solar energy. The ratio of these two energies represents the collector array efficiency which may be expressed as

$$\eta_c = Q_s/Q_i$$

where: η_c = collector array efficiency

Q_s = collected solar energy

Q_i = incident solar energy

The monthly efficiency computed by this method is listed in the column entitled "Collector Array Efficiency" in Table 5-5.

The second approach assumes the efficiency is based upon the incident solar energy during the periods of collection only.

Evaluating collector efficiency using operational incident energy and compensating for the difference between gross collector array area and the gross collector area yield operational collector efficiency. Operational collector efficiency, η_{co}, is computed as follows:

$$\eta_{co} = Q_s/(Q_{oi} \times \frac{A_p}{A_a})$$

where: Q_s = collected solar energy

Q_{oi} = operational incident energy

A_p = gross collector area (product of the number of collectors and the total envelope area of one unit)

A_a = gross collector array area (total area perpendicular to the solar flux vector, including all mounting, connecting and transport hardware

Note: The ratio $\frac{A_p}{A_a}$ is typically 1.0 for most collector array configurations.

The monthly efficiency computed by this method is listed in the column entitled "Operational Collector Array Efficiency" in Table 5-5. This latter efficiency term is not the same as collector efficiency as represented by the ASHRAE Standard 93-77 [5]. Both operational collector efficiency and the ASHRAE collector efficiency are defined as the ratio of actual useful energy collected to solar energy incident upon the collector and both use the same definition of collector area. However, the ASHRAE efficiency is determined from instantaneous evaluation under tightly controlled, steady-state test conditions, while the operational collector efficiency is determined from the actual conditions of daily solar energy system operation. Measured monthly values of operational incident energy and computed values of operational collector efficiency are presented in Table 5-5.

5.3.1.2 Storage

Storage performance data for the Chester West site for the reporting period is shown in Table 5-6. Results of analysis of solar energy losses during transport and storage are shown in Table 5-7. This table contains an evaluation of solar energy transport losses as a fraction of energy transported to subsystems.

During the reporting period, the average monthly solar energy delivered to storage was 2.58 million Btu. On the average, 1.48 million Btu of solar energy was delivered from storage to the DHW and space heating subsystems.

TABLE 5-6. STORAGE PERFORMANCE
CHESTER WEST

MONTH	ENERGY TO STORAGE (Million Btu)	ENERGY FROM STORAGE (Million Btu)	CHANGE IN STORED ENERGY (Million Btu)	STORAGE EFFICIENCY (%)	STORAGE AVERAGE TEMPERATURE (°F)	EFFECTIVE STORAGE HEAT LOSS COEFFICIENT (Btu/Hr -- °F)
SEP	3.05	0.75	0.14	29	158	N.A.
OCT	3.50	1.97	0.12	60	181	N.A.
NOV	1.50	1.71	-0.39	88	124	N.A.
DEC	3.52	*	0.05	*	96	N.A.
JAN	1.80	*	0.00	*	84	N.A.
FEB	2.08	*	0.07	*	89	N.A.
MAR	*	*	0.24	*	127	N.A.
TOTAL	15.45 (1)	4.43 (2)	0.23			
AVERAGE	2.58 (1)	1.48 (2)	0.03	53 (2)	123	N.A.

* - Denotes unavailable data
N.A. - Denotes not applicable data
(1) - Summation and average based on 6-month data: September, October, November, December 1978; January, February 1979
(2) - Average based on 3-month data: September, October, November 1978

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TABLE 5-7. SOLAR ENERGY LOSSES – STORAGE AND TRANSPORT
CHESTER WEST

	MONTH							
	SEP	OCT	NOV	DEC	JAN	FEB	MAR	TOTAL
1. SOLAR ENERGY (SE) COLLECTED MINUS SE DIRECTLY TO LOADS (million Btu)	3.46	4.27	1.85	3.80	1.99	2.21	3.74	21.32
2. SE TO STORAGE (million Btu)	3.05	3.50	1.50	3.52	1.80	2.08	*	15.45
3. LOSS – COLLECTOR TO STORAGE (%) $\frac{1-2}{1}$	12	18	19	7	10	6	*	---
4. CHANGE IN STORED ENERGY (million Btu)	0.14	0.12	-0.39	0.05	0.00	0.07	0.24	0.23
5. SOLAR ENERGY – STORAGE TO DHW SUBSYSTEM (million Btu)	0.75	1.58	0.51	*	*	*	*	*
6. SOLAR ENERGY – STORAGE TO SPACE HEATING SUBSYSTEM (million Btu)	0.00	0.39	1.20	1.17	0.77	0.86	0.73	5.12
7. SOLAR ENERGY – STORAGE TO SPACE COOLING SUBSYSTEM (million Btu)	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
8. LOSS FROM STORAGE (%) $\frac{2-(4+5+6+7)}{2}$	71	40	12	*	*	*	*	*
9. HOT WATER SOLAR ENERGY (HWSE) FROM STORAGE (million Btu)	0.75	1.58	0.51	*	*	*	*	*
10. LOSS – STORAGE TO HWSE (%) $\frac{5-9}{5}$	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
11. HEATING SOLAR ENERGY (HSE) FROM STORAGE (million Btu)	0.00	0.39	1.20	1.17	0.77	0.86	0.73	5.12
12. LOSS – STORAGE TO HSE (%) $\frac{6-11}{6}$	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.

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* - Denotes unavailable data
N.A. - Denotes not applicable data

The storage efficiency was 53 percent: This is calculated as the ratio of the sum of the energy removed from storage and the change in stored energy, to the energy delivered to storage. The average storage temperature for the period was 123°F.

Storage subsystem performance is evaluated by comparison of energy to storage, energy from storage, and the change in stored energy. The ratio of the sum of energy from storage and the change in stored energy, to the energy to storage is defined as storage efficiency, η_s. This relationship is expressed in the equation

$$\eta_s = (\Delta Q + Q_{so})/Q_{si}$$

where:

ΔQ = change in stored energy. This is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value)

Q_{so}= energy from storage. This is the amount of energy extracted by the load subsystem from the primary storage medium

Q_{si}= energy to storage. This is the amount of energy (both solar and auxiliary) delivered to the primary storage medium

An effective storage heat transfer coefficient (C) for the storage subsystem can be defined as follows:

$$C = (Q_{si}-Q_{so}-\Delta Q_s)/[\bar{T}_s - \bar{T}_a) \times t] \frac{\text{Btu}}{{}^\circ\text{F-hr}}$$

where:

C = effective storage heat transfer coefficient

Q_{si} = energy into storage

Q_{so} = energy from storage

ΔQ_s = change in stored energy

$\overline{T}_s$ = storage average temperature

$\overline{T}_a$ = average ambient temperature in the vicinity of storage

t = number of hours in the month

5.3.2 Domestic Hot Water (DHW) Subsystem

The DHW subsystem performance for the Chester West site for the reporting period is shown in Table 5-8. The DHW subsystem consumed a monthly average of 0.95[1] million Btu of solar energy and 0.47 million Btu of auxiliary electrical energy to satisfy an average monthly hot water load of 0.46 million Btu. The average solar fraction of this load was 74[1] percent.

The performance of the DHW subsystem is described by comparing the amount of solar energy supplied to the subsystem with the total energy required by the subsystem. The total energy required by the subsystem consists of both solar energy and auxiliary thermal energy. The DHW load is defined as the amount of energy required to raise the mass of water delivered by the DHW subsystem between the temperature at which it entered the subsystem and its delivery

(1) Weighted average based on 3-month data: September, October, and November (1978)

TABLE 5-8. DOMESTIC HOT WATER SUBSYSTEM PERFORMANCE

CHESTER WEST

MONTH	DOMESTIC HOT WATER LOAD (Million Btu)	ENERGY CONSUMED (Million Btu)				SOLAR FRACTION (%)
		SOLAR	AUXILIARY THERMAL	AUXILIARY		
				ELECTRICAL	FOSSIL	
SEP	0.23	0.75	0.04	0.04	N.A.	88
OCT	0.23	1.59	0.00	0.00	N.A.	100
NOV	0.44	0.51	0.46	0.46	N.A.	54
DEC	*	*	0.46	0.46	N.A.	*
JAN	0.39	*	0.66	0.66	N.A.	*
FEB	0.33	*	0.52	0.52	N.A.	*
MAR	1.11	*	1.15	1.15	N.A.	*
TOTAL	2.73 (2)	2.85 (3)	3.29	3.29	N.A.	
AVERAGE	0.46 (2)	0.95 (3)	0.47	0.47	N.A.	74 (1)(3)

* - Denotes unavailable data
N.A. - Denotes not applicable data
(1) - Weighted average based on load
(2) - Summation and average based on 6-month data: September, October, November 1978; January, February, March 1979
(3) - Summation and average based on 3-month data: September, October, November 1978

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temperature. The DHW solar fraction is defined as the portion of the DHW load which is supported by solar energy.

5.3.3 Space Heating Subsystem

The space heating subsystem performance for the Chester West site for the reporting period is shown in Table 5-9. The space heating subsystem consumed 5.12 million Btu of solar energy and 26.87 million Btu of auxiliary electrical energy to satisfy a space heating load of 33.09 million Btu. The solar fraction of this load was 15 percent.

The performance of the space heating subsystem is described by comparing the amount of solar energy supplied to the subsystem with the energy required to satisfy the total space heating load. The energy required to satisfy the total load consists of both solar energy and auxiliary thermal energy. The ratio of solar energy supplied to the load to the total load is defined as the heating solar fraction.

5.4 Operating Energy

Measured values of the Chester West solar energy system and subsystem operating energy for the reporting period are presented in Table 5-10. A total of 5.27 million Btu of operating energy was consumed by the entire system during the reporting period.

Operating energy for a solar energy system is defined as the amount of electrical energy required to support the subsystems without affecting their thermal state.

Total system operating energy for Chester West is the energy required to support the energy collection and storage subsystem (ECCS), DHW subsystem, and space heating subsystem. With reference to the system schematic (Figure 3-1), the ECCS operating energy includes pump P1, EP100. The DHW subsystem operating energy consists of pump P2, EP300. The space heating subsystem operating energy consists of pump P3, EP400, Fan B_1 EP401, and the heat pump fan power.

TABLE 5-9. SPACE HEATING SUBSYSTEM PERFORMANCE
CHESTER WEST

MONTH	SPACE HEATING LOAD (Million Btu)	ENERGY CONSUMED (Million Btu)				SOLAR FRACTION (%)
		SOLAR	AUXILIARY THERMAL	AUXILIARY		
				ELECTRICAL	FOSSIL	
SEPT	0.00	0.00	0.00	0.00	N.A.	N.A.
OCT	0.45	0.39	0.03	0.04	N.A.	86
NOV	2.37	1.20	0.86	0.93	N.A.	50
DEC	6.05	1.17	4.98	5.07	N.A.	19
JAN	13.39	0.77	10.81	11.50	N.A.	6
FEB	8.63	0.86	7.88	8.02	N.A.	10
MAR	2.20	0.73	1.22	1.31	N.A.	33
TOTAL	33.09	5.12	25.78	26.87	N.A.	
AVERAGE	4.73	.073	3.68	3.84	N.A.	15(1)

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N.A. - Denotes not applicable data
(1) - Weighted average based on load

CHESTER WEST

MONTH	ENERGY COLLECTION AND STORAGE OPERATING ENERGY (Million Btu)	DOMESTIC HOT WATER OPERATING ENERGY (Million Btu)	SPACE HEATING OPERATING ENERGY (Million Btu)	SPACE COOLING OPERATING ENERGY (Million Btu)	TOTAL SYSTEM OPERATING ENERGY (Million Btu)
SEPT	0.27	0.33	0.00	N.A.	0.60
OCT	0.32	0.41	0.01	N.A.	0.74
NOV	0.14	0.18	0.13	N.A.	0.45
DEC	0.22	0.18	0.51	N.A.	0.91
JAN	0.16	0.12	0.80	N.A.	1.08
FEB	0.16	0.17	0.49	N.A.	0.82
MAR	0.40	0.09	0.18	N.A.	0.67
TOTAL	1.67	1.48	2.12		5.27
AVERAGE	0.24	0.21	0.30		0.75

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N.A. - Denotes not applicable data

5.5 Energy Savings

Energy savings for the Chester West site for the reporting period are presented in Table 5-11. For this period the monthly average savings on electrical energy were 0.93[1] million Btu. An electrical energy expense of 3.31 million Btu was incurred during the reporting period for the operation of solar energy transportation pumps.

Solar energy system savings are realized whenever energy provided by the solar energy system is used to meet system demands which would otherwise be met by auxiliary energy sources. The operating energy required to provide solar energy to the load subsystems is subtracted from the solar energy contribution to determine net savings.

The auxiliary source at Chester West consists of a DHW heater (EP301), a heat pump (EP403), and electrical strip heaters (EP402). These units are considered to be 70 percent efficient for computational purposes.

[1] Weighted average based on 3-month data: September, October and November (1978)

TA... ENERGY SAVINGS
CHESTER WEST

MONTH	SOLAR ENERGY USED (Million Btu)	SOLAR ENERGY SAVINGS ATTRIBUTED TO (Million Btu)						SOLAR OPERATING ENERGY (Million Btu)	ENERGY SAVINGS (Million Btu)	
		SPACE HEATING		DOMESTIC HOT WATER		SPACE COOLING				
		ELECTRICAL	FOSSIL FUEL	ELECTRICAL	FOSSIL FUEL	ELECTRICAL	FOSSIL FUEL		ELECTRICAL	FOSSIL FUEL
SEP	0.75	0.00	N.A.	0.42	N.A.	N.A.	N.A.	0.60	0.15	N.A.
OCT	1.97	0.39	N.A.	1.18	N.A.	N.A.	N.A.	0.73	1.25	N.A.
NOV	1.71	1.18	N.A.	0.33	N.A.	N.A.	N.A.	0.34	1.38	N.A.
DEC	*	0.55	N.A.	*	N.A.	N.A.	N.A.	0.46	*	N.A.
JAN	*	0.41	N.A.	*	N.A.	N.A.	N.A.	0.31	*	N.A.
FEB	*	0.45	N.A.	*	N.A.	N.A.	N.A.	0.36	*	N.A.
MAR	*	0.33	N.A.	*	N.A.	N.A.	N.A.	0.51	*	N.A.
TOTAL	4.43(1)	3.31	N.A.	1.93(1)	N.A.	N.A.	N.A.	3.31	2.78(1)	N.A.
AVERAGE	1.48(1)	0.47	N.A.	0.64(1)	N.A.	N.A.	N.A.	0.47	0.93(1)	N.A.

* - Denotes unavailable data
N.A. - Denotes not applicable data
(1) - December through March excluded

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6. REFERENCES

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12.# Monthly Performance Report, Chester West, SOLAR/1030-79/03, Department of Energy, Washington, D.C., (March 1979).

Copies of these reports may be obtained from Technical Information Center, P. O. Box 62, Oak Ridge, Tennessee 37830.

APPENDIX A

DEFINITIONS OF PERFORMANCE FACTORS AND SOLAR TERMS

COLLECTOR ARRAY PERFORMANCE

The collector array performance is characterized by the amount of solar energy collected with respect to the energy available to be collected.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- OPERATIONAL INCIDENT ENERGY (SEOP) is the amount of solar energy incident on the collector array during the time that the collector loop is active (attempting to collect energy).

- COLLECTED SOLAR ENERGY (SECA) is the thermal energy removed from the collector array by the energy transport medium.

- COLLECTOR ARRAY EFFICIENCY (CAREF) is the ratio of the energy collected to the total solar energy incident on the collector array. It should be emphasized that this efficiency factor is for the collector array, and available energy includes the energy incident on the array when the collector loop is inactive. This efficiency must not be confused with the more common collector efficiency figures which are determined from instantaneous test data obtained during steady-state operation of a single collector unit. These efficiency figures are often provided by collector manufacturers or presented in technical journals to characterize the functional capability of a particular collector design. In general, the collector panel maximum efficiency factor will be significantly higher than the collector array efficiency reported here.

STORAGE PERFORMANCE

The storage performance is characterized by the relationships among the energy delivered to storage, removed from storage, and the subsequent change in the amount of stored energy.

- ENERGY TO STORAGE (STEI) is the amount of energy, both solar and auxiliary, delivered to the primary storage medium.

- ENERGY FROM STORAGE (STEO) is the amount of energy extracted by the load subsystems from the primary storage medium.

- CHANGE IN STORED ENERGY (STECH) is the difference in the estimated stored energy during the specified reporting period, as indicated by the relative temperature of the storage medium (either positive or negative value).

- STORAGE AVERAGE TEMPERATURE (TST) is the mass-weighted average temperature of the primary storage medium.

- STORAGE EFFICIENCY (STEFF) is the ratio of the sum of the energy removed from storage and the change in stored energy to the energy delivered to storage.

ENERGY COLLECTION AND STORAGE SUBSYSTEM

The Energy Collection and Storage Subsystem (ECSS) is composed of the collector array, the primary storage medium, the transport loops between these, and other components in the system design which are necessary to mechanize the collector and storage equipment.

- INCIDENT SOLAR ENERGY (SEA) is the total insolation available on the gross collector array area. This is the area of the collector array energy-receiving aperture, including the framework which is an integral part of the collector structure.

- AMBIENT TEMPERATURE (TA) is the average temperature of the outdoor environment at the site.

- ENERGY TO LOADS (SEL) is the total thermal energy transported from the ECSS to all load subsystems.

- AUXILIARY THERMAL ENERGY TO ECSS (CSAUX) is the total auxiliary energy supplied to the ECSS, including auxiliary energy added to the storage tank, heating devices on the collectors for freeze-protection, etc.

- ECSS OPERATING ENERGY (CSOPE) is the critical operating energy required to support the ECSS heat transfer loops.

HOT WATER SUBSYSTEM

The hot water subsystem is characterized by a complete accounting of the energy flow into and from the subsystem, as well as an accounting of internal energy. The energy into the subsystem is composed of auxiliary fossil fuel, and electrical auxiliary thermal energy, and the operating energy for the subsystem.

- HOT WATER LOAD (HWL) is the amount of energy required to heat the amount of hot water demanded at the site from the incoming temperature to the desired outlet temperature.

- SOLAR FRACTION OF LOAD (HWSFR) is the percentage of the load demand which is supported by solar energy.

- SOLAR ENERGY USED (HWSE) is the amount of solar energy supplied to the hot water subsystem.

- OPERATING ENERGY (HWOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to directly affect the thermal state of the subsystem.

- AUXILIARY THERMAL USED (HWAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid, or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.

- AUXILIARY FOSSIL FUEL (HWAF) is the amount of fossil fuel energy supplied directly to the subsystem.

- ELECTRICAL ENERGY SAVINGS (HWSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.

- FOSSIL FUEL SAVINGS (HWSVF) is the estimated difference between the fossil fuel energy requirements of the alternative conventional system (carrying the full load) and the actual fossil fuel energy requirements of the subsystem.

SPACE HEATING SUBSYSTEM

The space heating subsystem is characterized by performance factors accounting for the complete energy flow into the subsystem. The average building temperature is tabulated to indicate the relative performance of the subsystem in satisfying the space heating load and in controlling the temperature of the conditioned space.

- SPACE HEATING LOAD (HL) is the sensible energy added to the air in the building.

- SOLAR FRACTION OF LOAD (HSFR) is the fraction of the sensible energy added to the air in the building derived from the solar energy system.

- SOLAR ENERGY USED (HSE) is the amount of solar energy supplied to the space heating subsystem.

- OPERATING ENERGY (HOPE) is the amount of electrical energy required to support the subsystem, (e.g., fans, pumps, etc.) and which is not intended to directly affect the thermal state of the system.
- AUXILIARY THERMAL USED (HAT) is the amount of energy supplied to the major components of the subsystem in the form of thermal energy in a heat transfer fluid or its equivalent. This term also includes the converted electrical and fossil fuel energy supplied to the subsystem.
- AUXILIARY ELECTRICAL FUEL (HAE) is the amount of electrical energy supplied directly to the subsystem.
- ELECTRICAL ENERGY SAVINGS (HSVE) is the estimated difference between the electrical energy requirements of an alternative conventional system (carrying the full load) and the actual electrical energy required by the subsystem.
- BUILDING TEMPERATURE (TB) is the average heated space dry bulb temperature.

APPENDIX B

SOLAR ENERGY SYSTEM PERFORMANCE EQUATIONS

CHESTER WEST

INTRODUCTION

Solar energy system performance is evaluated by performing energy balance calculations on the system and its major subsystems. These calculations are based on physical measurement data taken from each sensor every 320 seconds. This data is then mathematically combined to determine the hourly, daily, and monthly performance of the system. This appendix describes the general computational methods and the specific energy balance equations used for this site.

Data samples from the system measurements are integrated to provide discrete approximations of the continuous functions which characterize the system's dynamic behavior. This integration is performed by summation of the product of the measured rate of the appropriate performance parameters and the sampling interval over the total time period of interest.

There are several general forms of integration equations which are applied to each site. These general forms are exemplified as follows: The total solar energy available to the collector array is given by

$$\text{SOLAR ENERGY AVAILABLE} = (1/60)\ \Sigma\ [\text{I001} \times \text{AREA}] \times \Delta\tau$$

where I001 is the solar radiation measurement provided by the pyranometer in Btu per square foot per hour, AREA is the area of the collector array in square feet, $\Delta\tau$ is the sampling interval in minutes, and the factor (1/60) is included to correct the solar radiation "rate" to the proper units of time.

Similarly, the energy flow within a system is given typically by

$$\text{COLLECTED SOLAR ENERGY} = \Sigma\ [\text{M100} \times \Delta H] \times \Delta\tau$$

where M100 is the mass flow rate of the heat transfer fluid in lb_m/min and ΔH is the enthalpy change, in Btu/lb_m, of the fluid as it passes through the heat exchanging component.

For a liquid system ΔH is generally given by

$$\Delta H = \overline{C}_p\ \Delta T$$

where $\overline{C}_p$ is the average specific heat, in Btu/(lb_m-°F), of the heat transfer fluid and ΔT, in °F, is the temperature differential across the heat exchanging component.

For an air system ΔH is generally given by

$$\Delta H = H_a(T_{out}) - H_a(T_{in})$$

where $H_a(T)$ is the enthalpy, in Btu/lb_m, of the transport air evaluated at the inlet and outlet temperatures of the heat exchanging component.

$H_a(T)$ can have various forms, depending on whether or not the humidity ratio of the transport air remains constant as it passes through the heat exchanging component.

For electrical power, a general example is

$$\text{ECSS OPERATING ENERGY} = (3413/60)\ \Sigma\ [\text{EP100}] \times \Delta\tau$$

where EP100 is the power required by electrical equipment in kilowatts and the two factors (1/60) and 3413 correct the data to Btu/min.

These equations are comparable to those specified in "Thermal Data Requirements and Performance Evaluation Procedures for the National Solar Heating and Cooling Demonstration Program." This document was prepared by an interagency committee of the Government, and presents guidelines for thermal performance evaluation.

Performance factors are computed for each hour of the day. Each integration process, therfore, is performed over a period of one hour. Since long-term performance data is desired, it is necessary to build these hourly performance factors to daily values. This is accomplished, for energy parameters, by summing the 24 hourly values. For temperatures, the hourly values are averaged. Certain special factors, such as efficiencies, require appropriate handling to properly weight each hourly sample for the daily value computation. Similar procedures are required to convert daily values to monthly values.

EQUATIONS USED TO GENERATE MONTHLY PERFORMANCE VALUES

NOTE: SENSOR IDENTIFICATION (MEASUREMENT) NUMBERS REFERENCE SYSTEM SCHEMATIC FIGURE 3-1

AVERAGE AMBIENT TEMPERATURE (°F)

$$TA = (1/60) \times \Sigma\ T001 \times \Delta\tau$$

AVERAGE BUILDING TEMPERATURE (°F)

$$TB = (1/60) \times T600 \times \Delta\tau$$

DAYTIME AVERAGE AMBIENT TEMPERATURE (°F)

$$TDA = (1/360) \times \Sigma\ T001 \times \Delta\tau$$

FOR $\pm$ 3 HOURS FROM SOLAR NOON

HOT WATER LOAD (BTU)

$$HWL = \Sigma\ [M301 * HWD\ (T351,T301)] * \Delta\tau$$

SOLAR ENERGY TO DHW TANK (BTU)

$$HWSE = \Sigma\ [M300 * HWD\ (T300,T350)] * \Delta\tau$$

INCIDENT SOLAR ENERGY PER SQUARE FOOT (BTU/FT^2)

$$SE = (1/60) \times \Sigma\ I001 \times \Delta\tau$$

INCIDENT SOLAR ENERGY ON COLLECTOR ARRAY (BTU)

$$SEA = (1/60) \times \Sigma\ [I001 \times CLAREA] \times \Delta\tau$$

OPERATIONAL INCIDENT SOLAR ENERGY (BTU)

$$SEOP = (1/60) \times \Sigma\ [I001 \times CLAREA] \times \Delta\tau$$

WHEN THE COLLECTOR LOOP IS ACTIVE

SOLAR ENERGY COLLECTED BY THE ARRAY (BTU)

$$SECA = \Sigma\ [M100 * CPC(T100 + T150)/2 * (T150 - T100)] * \Delta\tau$$

SOLAR ENERGY TO STORAGE

$$STEI = \Sigma\ [M100 * CP61\ ((T1o1 + T151/2) * (T101 - T151)] * \Delta\tau$$

ENERGY FROM STORAGE TO DHW LOAD (BTU)

$STEO2 = \Sigma$ [M300 * HWD CT300,T350) * $\Delta\tau$

ENERGY FROM STORAGE TO SPACE HEATING LOAD (BTU)

$STEO1 = \Sigma$ [M400 * HWD (T400,T450) * $\Delta\tau$

ENERGY FROM STORAGE TO SPACE HEATING LOAD (BTU) DEFAULT

$STEO1AIR = \Sigma$ [M401 * HRF * (T451 - T401)] * $\Delta\tau$

USED IN PLACE OF STEO1 WHEN W400 PROVIDED INVALID DATA

ENERGY FROM STORAGE (BTU)

STEO = STEO1 + STEO2

AVERAGE TEMPERATURE OF STORAGE

$TST = (1/60) \times \Sigma [(T200 + T201 + T202)/3] \times \Delta\tau$

ECSS OPERATING ENERGY (BTU)

$CSOPE = 56.86833 \times \Sigma EP100 \times \Delta\tau$

HOT WATER CONSUMED (GALLONS)

$HWCSM = \Sigma W301 \times \Delta\tau$

HOT WATER SUBSYSTEM OPERATING ENERGY (BTU)

$HWOPE = 56.86833 \times \Sigma EP300 \times \Delta\tau$

HOT WATER AUXILIARY ELECTRIC ENERGY (BTU)

$HWAE = 56.86833 \times \Sigma EP301 \times \Delta\tau$

SPACE HEATING OPERATING ENERGY, SOLAR AND BLOWER (BTU)

$HOPEX = \Sigma [56.86833 * (EP400 + EP401)] * \Delta\tau$

WHEN IN HEATING MODE (T453 - T401) > 1

HEAT PUMP FAN ELECTRICAL (BTU)

$FP = 0.5 * \Sigma \Delta\tau$

WHEN (T452 - T451) > 1 AND EP403 > 0

SPACE HEATING OPERATING ENERGY, SOLAR, BLOWER AND HEAT PUMP FAN (BTU)

HOPE = HOPEX + FP

WHEN (T452 - T451) > 1 AND EP403 > 0

SPACE HEATING, HEAT PUMP (BTU)

HAE1 = 56.86833 * Σ (EP403 - FP) * $\Delta\tau$

WHEN (T452 - T451) > 1 AND EP403 > 0

SPACE HEATING, HEAT STRIPS (BTU)

HAE2 - 56.86833 * Σ EP402 * $\Delta\tau$

SPACE HEATING, AUXILIARY ELECTRICAL ENERGY (BTU)

HAE = HAE1 + HAE2

SPACE HEATING, OPERATING ENERGY, SOLAR POWER

HOPE1 = 56.86833 * Σ EP400 * $\Delta\tau$

SERVICE HOT WATER TEMPERATURE (°F)

THW = (1/60) * (T351 * M301)/M301) * $\Delta\tau$

WHEN WATER IS BEING DRAWN

SERVICE SUPPLY WATER TEMPERATURE (°F)

TSW = (1/60) * (T301 * M301) * $\Delta\tau$

WHEN WATER IS BEING DRAWN

SPACE HEATING AUXILIARY THERMAL ENERGY (BTU)

HAT = 0.7 * HAE1 + HAE2

COLLECTED SOLAR ENERGY (BTU)

SEC = SECA/CLAREA

ENERGY TO STORAGE (BTU)

STEI + Σ M100 * CP61 ((T101 + T151)/2) * (T101 - T151) * $\Delta\tau$

CHANGE IN STORED ENERGY (BTU)

STECH - STOCAP * (RHOTSTL * CPTSTL * TSTL - RHOTSTLP * CPTSTLP * TSTLP)

STOCAP EQUALS STORAGE CAPACITY. TSTL IS THE LATEST TST AND TSTLP IS THE TST JUST PREVIOUS.

ENERGY DELIVERED TO LOAD SUBSYSTEMS FROM ECSS (BTU)

CSEO = STEO

STORING EFFICIENCY

STEFF = (STECH + STEO)/STEI

ECSS SOLAR CONVERSION EFFICIENCY

CSCEF = CSEO/SEA

HOT WATER AUXILIARY THERMAL ENERGY (BTU)

HWAT = HWAE

HOT WATER SOLAR FRACTION

HWSFR = FRACTION OF DELIVERED HOT WATER LOAD DERIVED FROM SOLAR SOURCES AFTER PRO-RATING STORAGE LOSSES TO SOLAR AND AUXILIARY SOURCES

HOT WATER ELECTRICAL ENERGY SAVINGS (BTU)

HWSVE = HWSE - HWOPE

SOLAR ENERGY TO SPACE HEATING (BTU)

HSE = STEO1

SPACE HEATING LOAD, HEAT PUMP (BTU)

$HLHP = \Sigma\ M401 * HRF * (T452 - T451) * \Delta\tau$

WHEN $(T452 - T451) > 1$ AND $EP403 > 0$

SPACE HEATING LOAD (BTU)

HL = HLHP + HAE2 + HSE

SPACE HEATING SYSTEM ELECTRICAL ENERGY SAVINGS (BTU)

HSVE = (HSE/HPFRAC * HPCOPH + (1 - HPFRAC))) - HOPE1

SYSTEM LOAD

SYSL = HL + HWL

SOLAR ENERGY TO LOAD

SEL = STEO

SPACE HEATING SOLAR FRACTION

HSFR = 100 x (HSE/HL)

SOLAR FRACTION OF SYSTEM LOAD

SFR = (HL x HSFR + HWL x HWSFR)/SYSL

AUXILIARY THERMAL ENERGY TO LOADS

AXT = HWAT + HAT

AUXILIARY ELECTRICAL ENERGY TO LOADS

AXE = HAE + HWAE

SYSTEM OPERATING ENERGY

SYSOPE = HWOPE + HOPE + CSOPE

TOTAL ENERGY CONSUMED

TECSM = SYSOPE + AXE + SECA

TOTAL ELECTRICAL ENERGY SAVINGS

TSVE = HWSVE + HSVE - CSOPE

SYSTEM PERFORMANCE FACTOR

SYSPF = SYSL/((AXE + SYSOPE) x 3.33)

APPENDIX C

LONG-TERM AVERAGE WEATHER CONDITIONS

This appendix contains a table which lists the long-term average weather conditions for each month of the year for this site.

SITE: CHESTER WEST 78.

LOCATION: HUNTSVILLE AL

ANALYST: N. LABBE

FDRIVE NO.: 12.

COLLECTOR TILT: 49.00 (DEGREES)

COLLECTOR AZIMUTH: 0.0 (DEGREES)

LATITUDE: 34.40 (DEGREES)

RUN DATE: 6/04/79

MONTH	HOBAR	HBAR	KBAR	RBAR	SBAR	HDD	CDD	TBAR
JAN	1625.	649.	0.39936	1.520	987.	747	0	41.
FEB	2063.	900.	0.43614	1.329	1195.	605	6	44.
MAR	2605.	1220.	0.46856	1.115	1361.	461	21	51.
APR	3137.	1615.	0.51474	0.924	1492.	145	46	62.
MAY	3487.	1844.	0.52862	0.797	1470.	32	174	70.
JUN	3620.	1939.	0.53569	0.745	1445.	0	357	77.
JUL	3546.	1847.	0.52087	0.769	1421.	0	450	80.
AUG	3265.	1729.	0.52962	0.867	1498.	0	434	79.
SEP	2792.	1431.	0.51244	1.041	1490.	11	248	73.
OCT	2218.	1165.	0.52539	1.301	1516.	159	72	62.
NOV	1725.	793.	0.45948	1.524	1208.	441	0	50.
DEC	1501.	597.	0.39783	1.593	951.	701	0	42.

LEGEND:

HOBAR ==> MONTHLY AVERAGE DAILY EXTRATERRESTRIAL RADIATION (IDEAL) IN BTU/DAY-FT2.

HBAR ==> MONTHLY AVERAGE DAILY RADIATION (ACTUAL) IN BTU/DAY-FT2.

KBAR ==> RATIO OF HBAR TO HOBAR.

RBAR ==> RATIO OF MONTHLY AVERAGE DAILY RADIATION ON TILTED SURFACE TO THAT ON A HORIZONTAL SURFACE FOR EACH MONTH (I.E., MULTIPLIER OBTAINED BY TILTING).

SBAR ==> MONTHLY AVERAGE DAILY RADIATION ON A TILTED SURFACE (I.E., RBAR * HBAR) IN BTU/DAY-FT2.

HDD ==> NUMBER OF HEATING DEGREE DAYS PER MONTH.

CDD ==> NUMBER OF COOLING DEGREE DAYS PER MONTH.

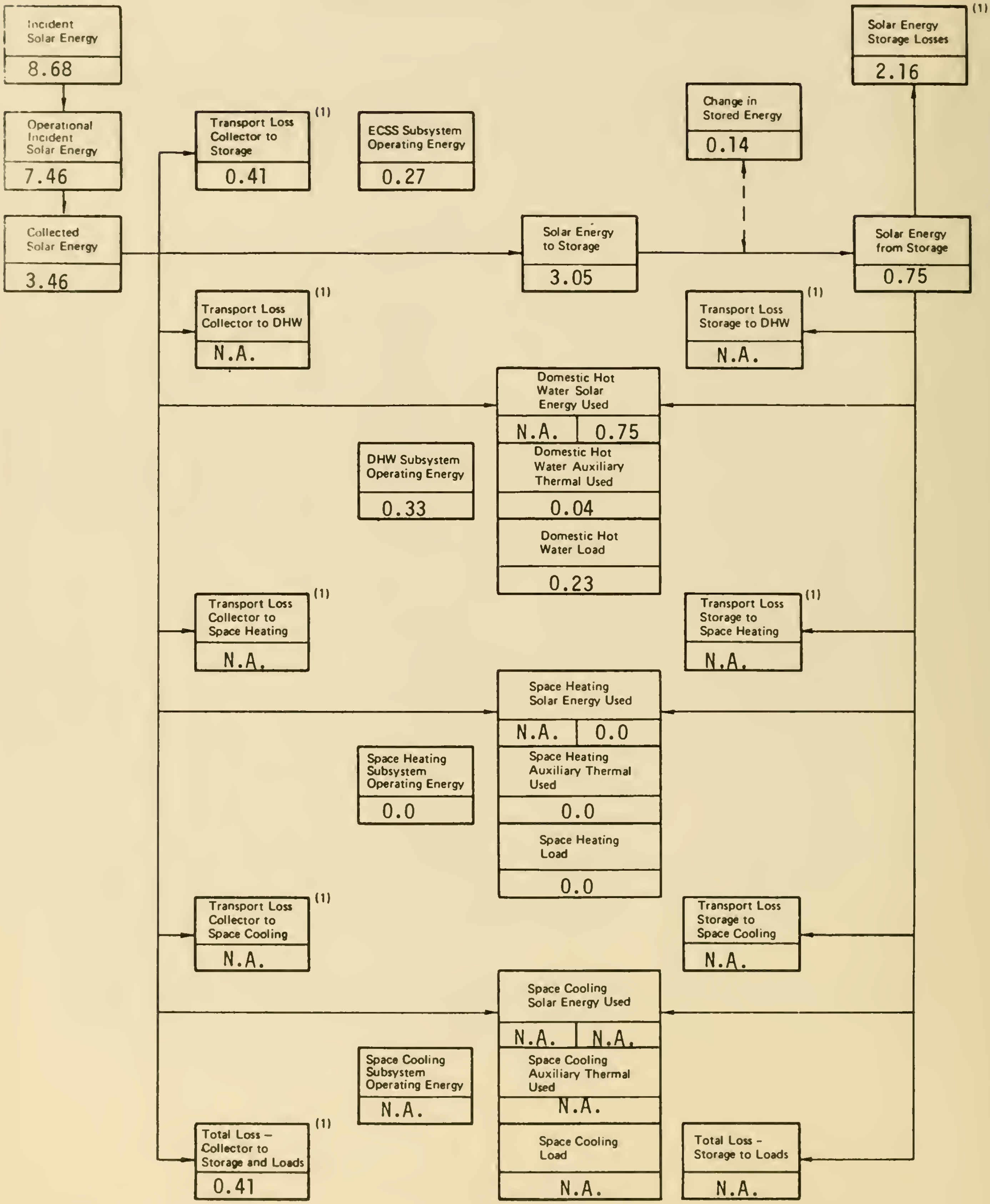
TBAR ==> AVERAGE AMBIENT TEMPERATURE IN DEGREES FAHRENHEIT.

APPENDIX D

MONTHLY SOLAR ENERGY DISTRIBUTION FLOWCHARTS

The flowcharts in this appendix depict the quantity of solar energy corresponding to each major component or characteristic of the Chester West solar energy system for 7 months of the reporting period. Each monthly flowchart represents a solar energy balance as the total input equals the total output.

FIGURE D-1. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - SEPTEMBER 1978
CHESTER WEST

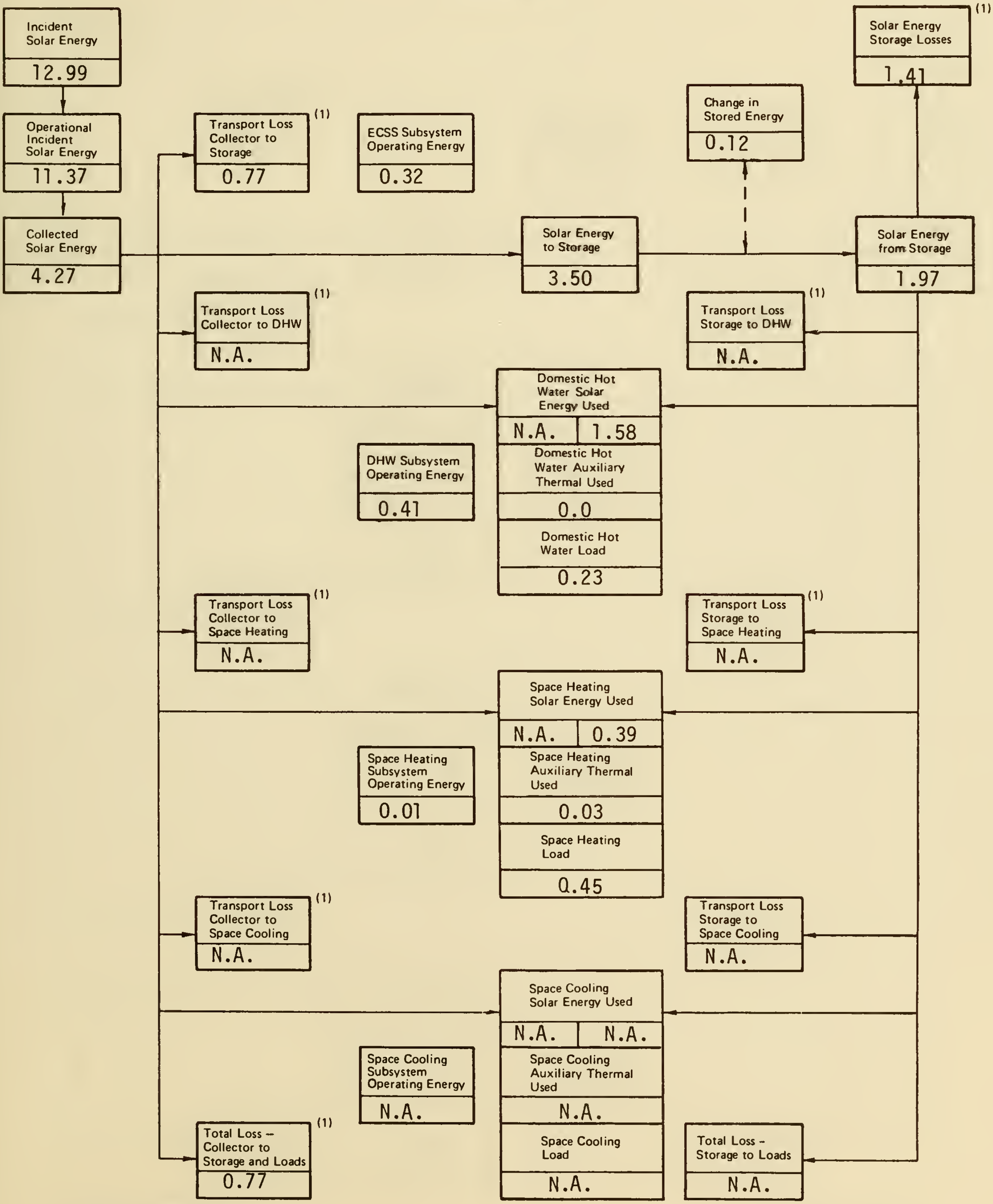


• Denotes Unavailable Data
N.A. denotes not applicable data
(1) May contribute to offset of space heating load (if known – see text for discussion)

8002

FIGURE D-2. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - OCTOBER 1978

CHESTER WEST



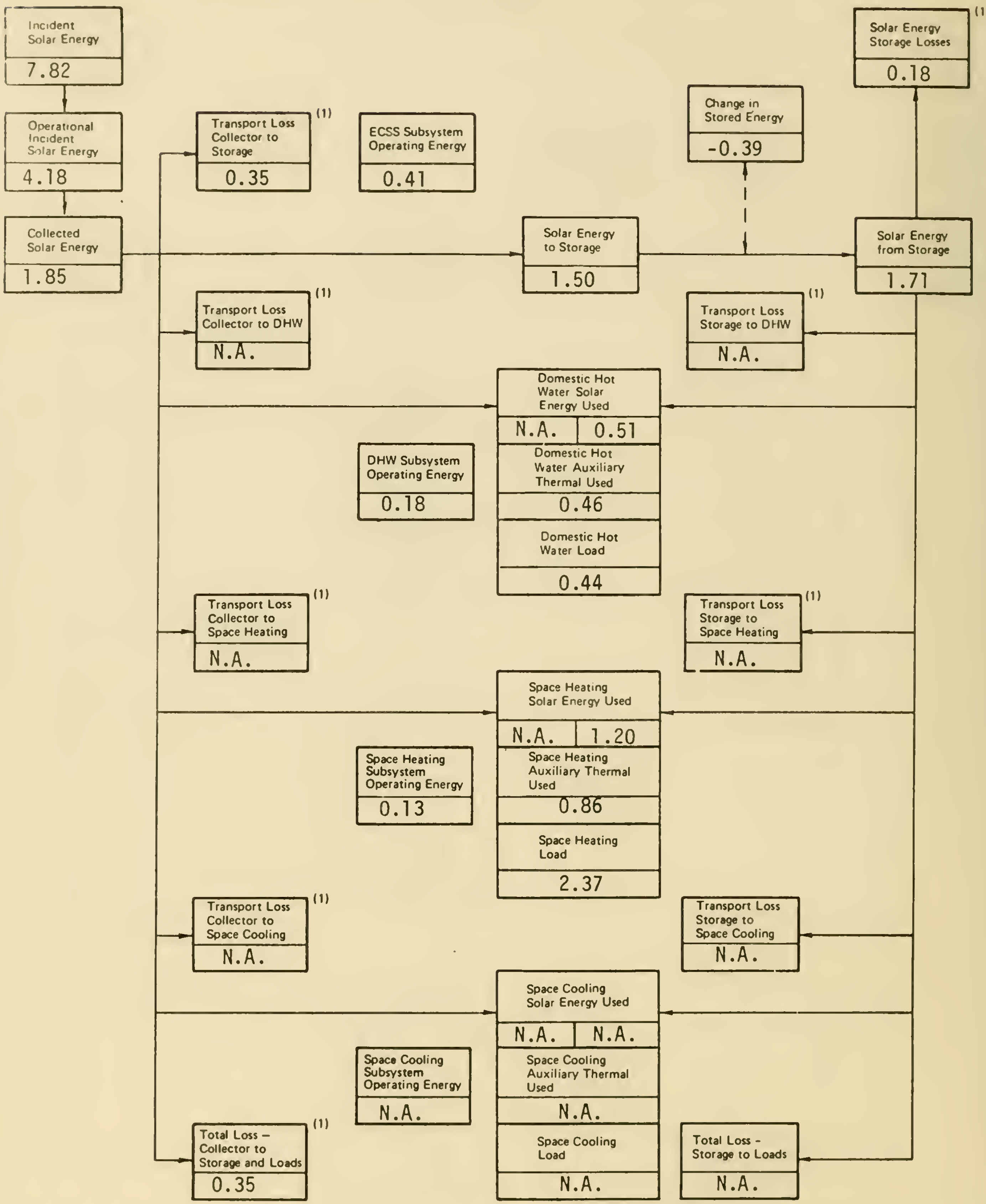
* Denotes Unavailable Data

N.A. denotes not applicable data

(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

FIGURE D-3. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - NOVEMBER 1978
CHESTER WEST

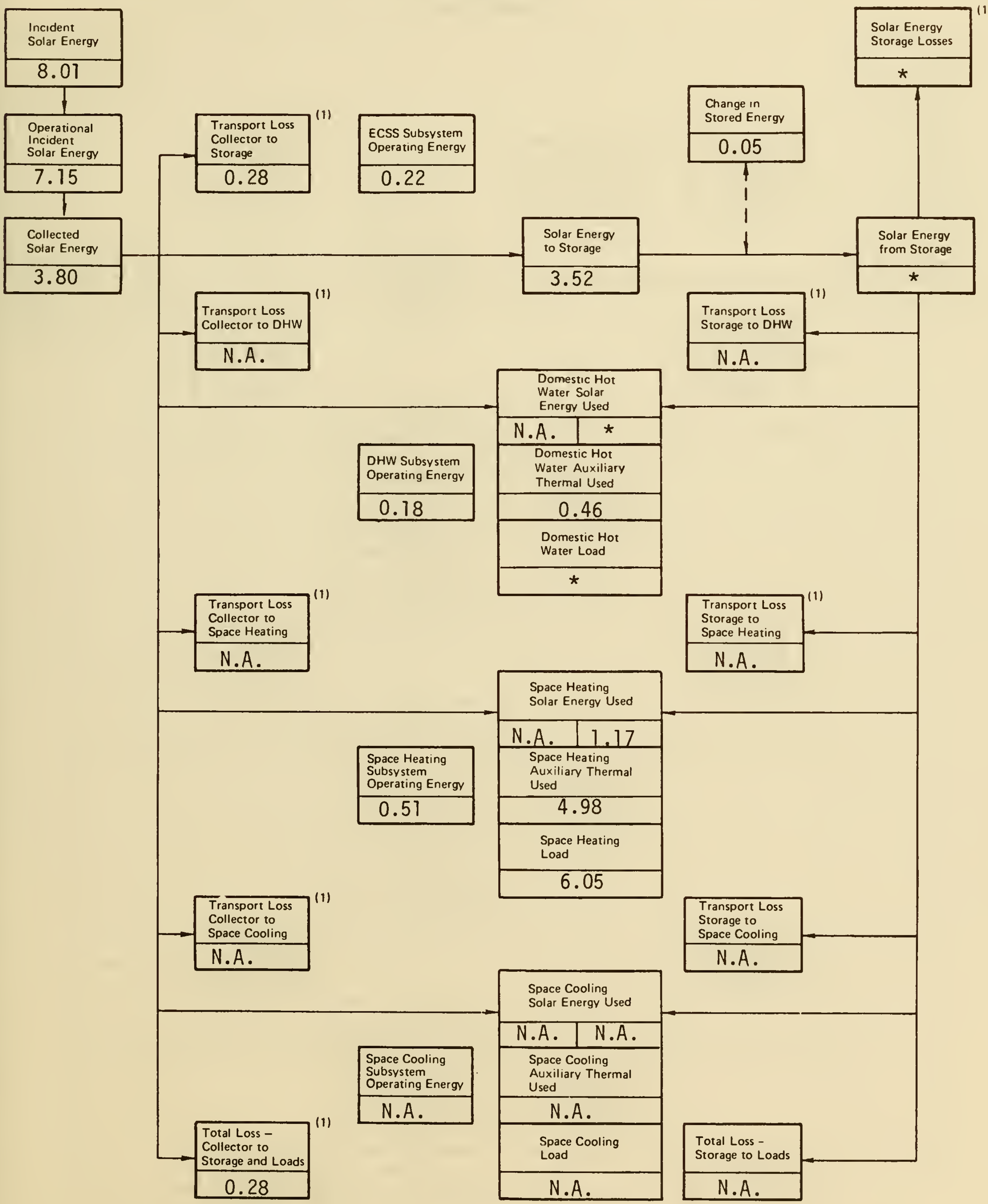


• Denotes Unavailable Data
N.A. denotes not applicable data
(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

FIGURE D-4. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - DECEMBER 1978

CHESTER WEST



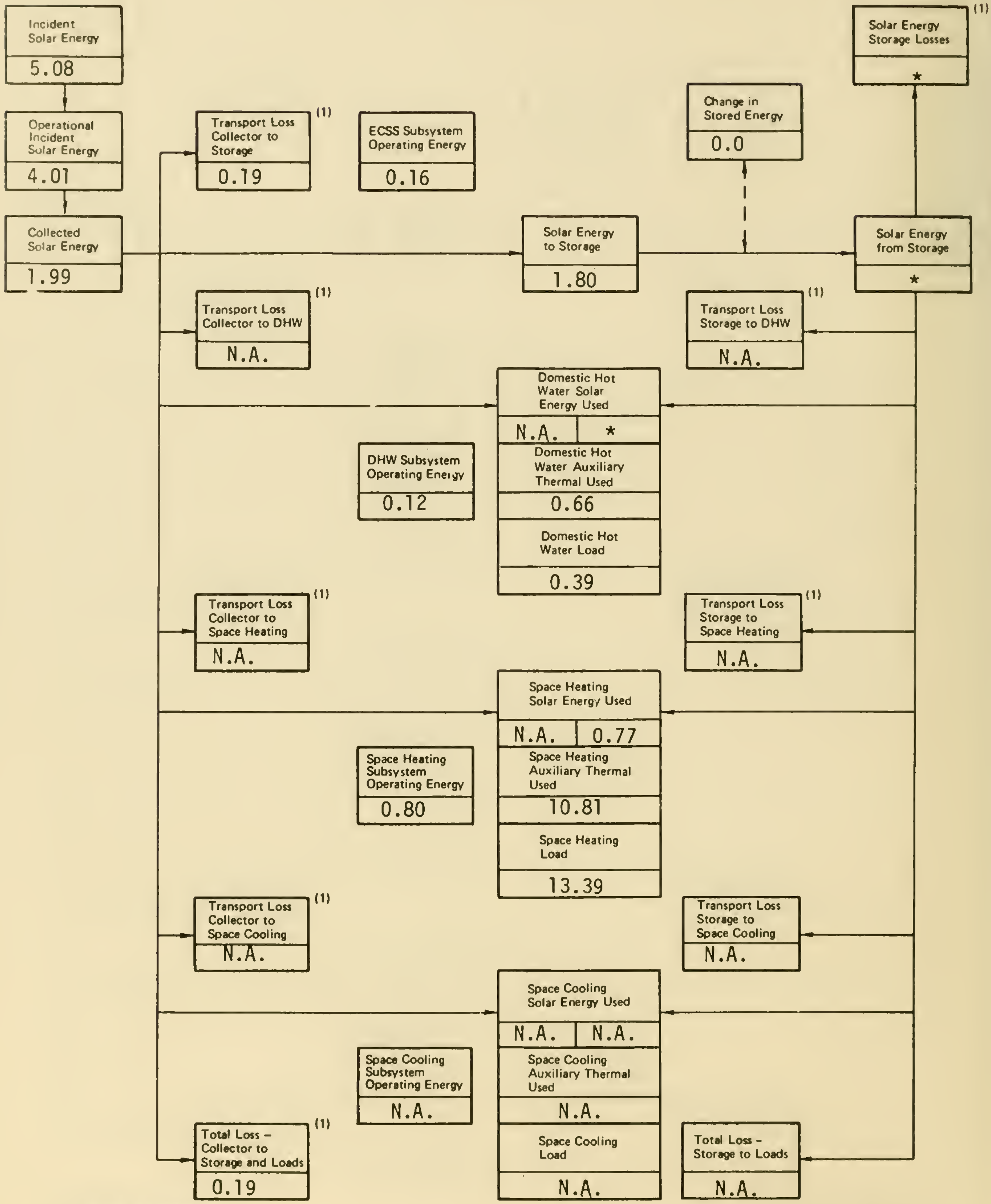
* Denotes Unavailable Data

N.A. denotes not applicable data

(1) May contribute to offset of space heating load (if known – see text for discussion)

S002

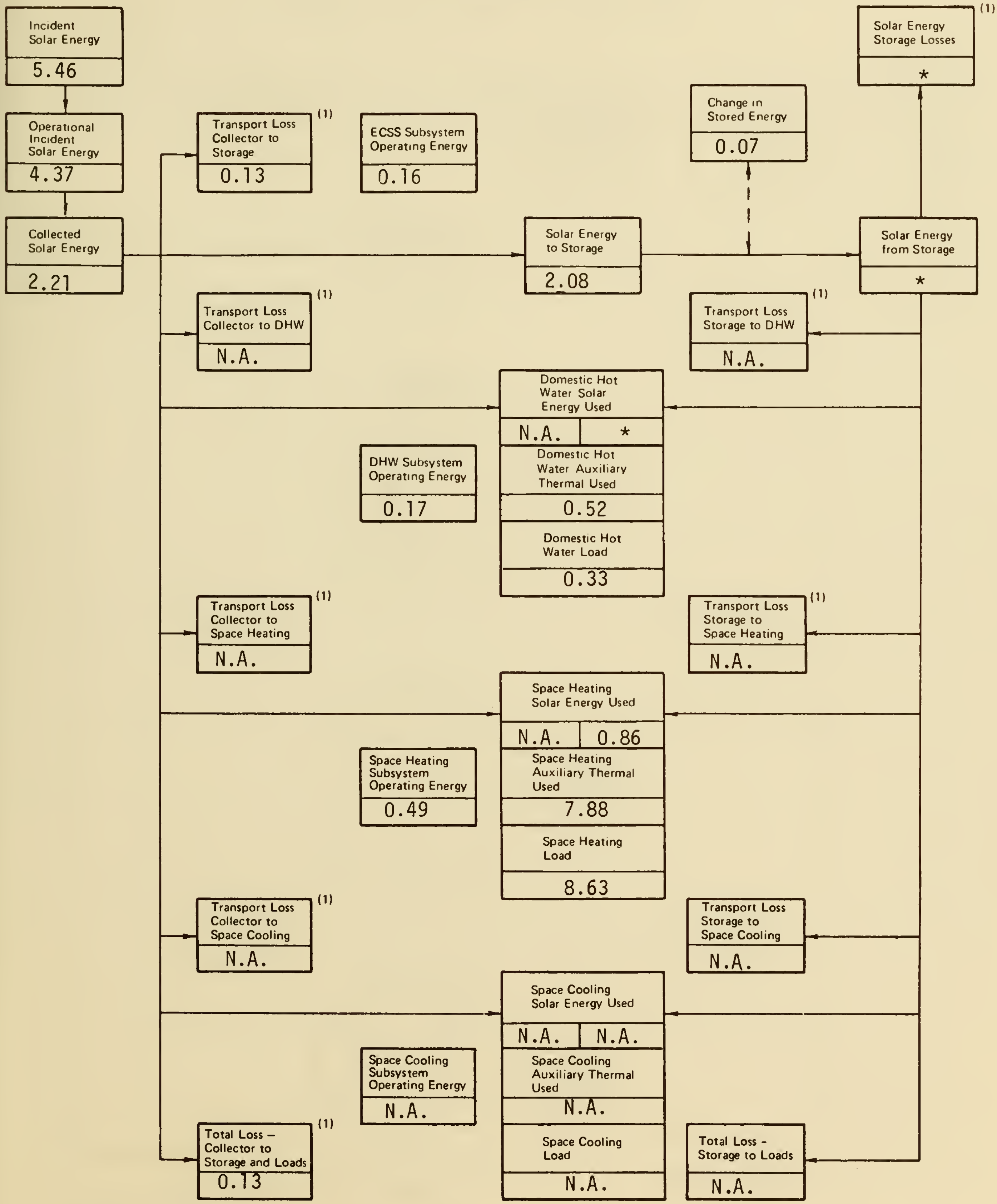
FIGURE D-5. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - JANUARY 1979
CHESTER WEST



* Denotes Unavailable Data
N.A. denotes not applicable data
(1) May contribute to offset of space heating load (if known – see text for discussion)

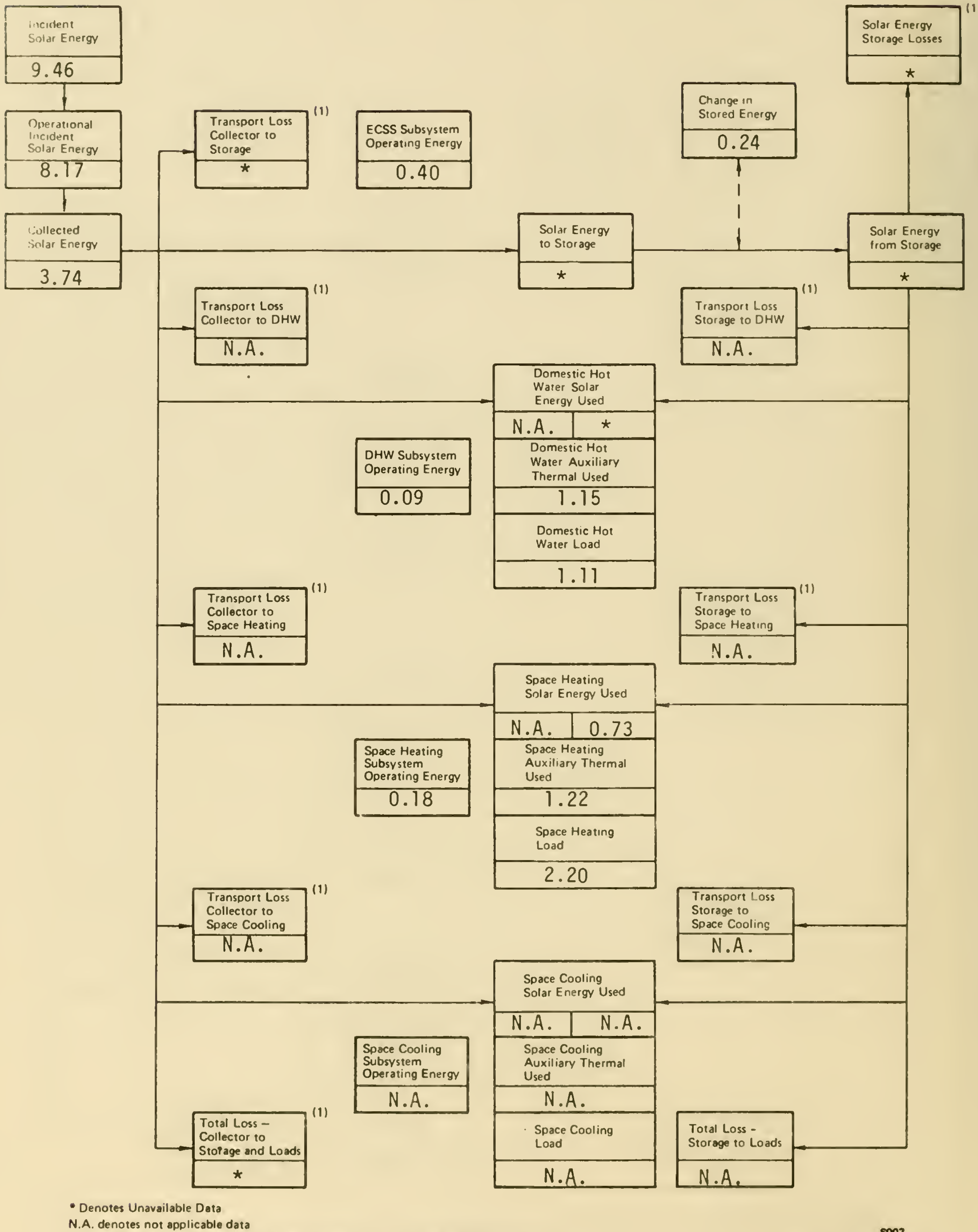
S002

FIGURE D-6. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - FEBRUARY 1979
CHESTER WEST



* Denotes Unavailable Data
N.A. denotes not applicable data
(1) May contribute to offset of space heating load (if known – see text for discussion)

FIGURE D-7. SOLAR ENERGY (MILLION BTU) DISTRIBUTION FLOWCHART - MARCH 1979
CHESTER WEST



* Denotes Unavailable Data
N.A. denotes not applicable data
(1) May contribute to offset of space heating load (if known – see text for discussion)

APPENDIX E

MONTHLY SOLAR ENERGY DISTRIBUTIONS

The data tables provided in this appendix present an indication of solar energy distribution, intentional and unintentional, in the Chester West solar energy system. Tables are provided for 7 months of the reporting period.

TABLE E-1. SOLAR ENERGY DISTRIBUTION - SEPTEMBER 1978

CHESTER WEST

- 3.46 million Btu (100%) TOTAL SOLAR ENERGY COLLECTED
    - 0.75 million Btu (22%) SOLAR ENERGY TO LOADS
        - 0.75 million Btu (22%) SOLAR ENERGY TO DHW SUBSYSTEM
        - 0.0 million Btu (%) SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
        - N.A. million Btu (%) SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
    - 2.57 million Btu (74%) SOLAR ENERGY LOSSES
        - 2.16 million Btu (62%) SOLAR ENERGY LOSS FROM STORAGE
        - 0.41 million Btu (12%) SOLAR ENERGY LOSS IN TRANSPORT
            - 0.41 million Btu (12%) COLLECTOR TO STORAGE LOSS
            - N.A. million Btu (%) COLLECTOR TO LOAD LOSS
                - N.A. million Btu (%) COLLECTOR TO DHW LOSS
                - N.A. million Btu (%) COLLECTOR TO SPACE HEATING LOSS
                - N.A. million Btu (%) COLLECTOR TO SPACE COOLING LOSS
            - N.A. million Btu (%) STORAGE TO LOAD LOSS
                - N.A. million Btu (%) STORAGE TO DHW LOSS
                - N.A. million Btu (%) STORAGE TO SPACE HEATING LOSS
                - N.A. million Btu (%) STORAGE TO SPACE COOLING LOSS
    - 0.14 million Btu (4%) SOLAR ENERGY STORAGE CHANGE

N.A. - Denotes not applicable data

TABLE E-2. SOLAR ENERGY DISTRIBUTION - OCTOBER 1978
CHESTER WEST

4.27	100%	million Btu	TOTAL SOLAR ENERGY COLLECTED
1.97	46%	million Btu	SOLAR ENERGY TO LOADS
1.58	37 %	million Btu	SOLAR ENERGY TO DHW SUBSYSTEM
0.39	9%	million Btu	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	%	million Btu	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
2.18	51%	million Btu	SOLAR ENERGY LOSSES
1.41	33%	million Btu	SOLAR ENERGY LOSS FROM STORAGE
0.77	18%	million Btu	SOLAR ENERGY LOSS IN TRANSPORT
0.77	18%	million Btu	COLLECTOR TO STORAGE LOSS
N.A.	%	million Btu	COLLECTOR TO LOAD LOSS
N.A.	%	million Btu	COLLECTOR TO DHW LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE HEATING LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE COOLING LOSS
N.A.	%	million Btu	STORAGE TO LOAD LOSS
N.A.	%	million Btu	STORAGE TO DHW LOSS
N.A.	%	million Btu	STORAGE TO SPACE HEATING LOSS
N.A.	%	million Btu	STORAGE TO SPACE COOLING LOSS
0.12	3%	million Btu	SOLAR ENERGY STORAGE CHANGE

N.A. - Denotes not applicable data

TABLE E-3. SOLAR ENERGY DISTRIBUTION - NOVEMBER 1978

Chester West

1.85 million Btu	100%	TOTAL SOLAR ENERGY COLLECTED
1.71 million Btu	92%	SOLAR ENERGY TO LOADS
0.51 million Btu	27%	SOLAR ENERGY TO DHW SUBSYSTEM
1.20 million Btu	65%	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A. million Btu	%	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
0.53 million Btu	29%	SOLAR ENERGY LOSSES
0.18 million Btu	10%	SOLAR ENERGY LOSS FROM STORAGE
0.35 million Btu	19%	SOLAR ENERGY LOSS IN TRANSPORT
0.35 million Btu	19%	COLLECTOR TO STORAGE LOSS
N.A. million Btu	%	COLLECTOR TO LOAD LOSS
N.A. million Btu	%	COLLECTOR TO DHW LOSS
N.A. million Btu	%	COLLECTOR TO SPACE HEATING LOSS
N.A. million Btu	%	COLLECTOR TO SPACE COOLING LOSS
N.A. million Btu	%	STORAGE TO LOAD LOSS
N.A. million Btu	%	STORAGE TO DHW LOSS
N.A. million Btu	%	STORAGE TO SPACE HEATING LOSS
N.A. million Btu	%	STORAGE TO SPACE COOLING LOSS
-0.39 million Btu	-21%	SOLAR ENERGY STORAGE CHANGE

N.A. - Denotes not applicable data

TABLE E-4. SOLAR ENERGY DISTRIBUTION - DECEMBER 1978
CHESTER WEST

3.80	100%	million Btu	TOTAL SOLAR ENERGY COLLECTED
*	%	million Btu	SOLAR ENERGY TO LOADS
*	%	million Btu	SOLAR ENERGY TO DHW SUBSYSTEM
1.17	31%	million Btu	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	%	million Btu	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
*	%	million Btu	SOLAR ENERGY LOSSES
*	%	million Btu	SOLAR ENERGY LOSS FROM STORAGE
0.28	7%	million Btu	SOLAR ENERGY LOSS IN TRANSPORT
*	%	million Btu	COLLECTOR TO STORAGE LOSS
*	%	million Btu	COLLECTOR TO LOAD LOSS
*	%	million Btu	COLLECTOR TO DHW LOSS
*	%	million Btu	COLLECTOR TO SPACE HEATING LOSS
*	%	million Btu	COLLECTOR TO SPACE COOLING LOSS
*	%	million Btu	STORAGE TO LOAD LOSS
*	%	million Btu	STORAGE TO DHW LOSS
*	%	million Btu	STORAGE TO SPACE HEATING LOSS
*	%	million Btu	STORAGE TO SPACE COOLING LOSS
0.05	1%	million Btu	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data

TABLE E-5. SOLAR ENERGY DISTRIBUTION - JANUARY 1979
CHESTER WEST

1.99	100%	million Btu	TOTAL SOLAR ENERGY COLLECTED
*	%	million Btu	SOLAR ENERGY TO LOADS
*	%	million Btu	SOLAR ENERGY TO DHW SUBSYSTEM
0.77	39%	million Btu	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	%	million Btu	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
*	%	million Btu	SOLAR ENERGY LOSSES
*	%	million Btu	SOLAR ENERGY LOSS FROM STORAGE
0.19	10%	million Btu	SOLAR ENERGY LOSS IN TRANSPORT
0.19	9%	million Btu	COLLECTOR TO STORAGE LOSS
N.A.	%	million Btu	COLLECTOR TO LOAD LOSS
N.A.	%	million Btu	COLLECTOR TO DHW LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE HEATING LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE COOLING LOSS
N.A.	%	million Btu	STORAGE TO LOAD LOSS
N.A.	%	million Btu	STORAGE TO DHW LOSS
N.A.	%	million Btu	STORAGE TO SPACE HEATING LOSS
N.A.	%	million Btu	STORAGE TO SPACE COOLING LOSS
0.0	(±) 0%	million Btu	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data

TABLE E-6. SOLAR ENERGY DISTRIBUTION - FEBRUARY 1979
CHESTER WEST

- 2.21 million Btu / 100% — TOTAL SOLAR ENERGY COLLECTED
  - * million Btu / % — SOLAR ENERGY TO LOADS
    - * million Btu / % — SOLAR ENERGY TO DHW SUBSYSTEM
    - 0.86 million Btu / 39% — SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
    - N.A. million Btu / % — SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
  - * million Btu / % — SOLAR ENERGY LOSSES
    - * million Btu / % — SOLAR ENERGY LOSS FROM STORAGE
    - 0.13 million Btu / 6% — SOLAR ENERGY LOSS IN TRANSPORT
      - 0.13 million Btu / 6% — COLLECTOR TO STORAGE LOSS
      - N.A. million Btu / % — COLLECTOR TO LOAD LOSS
        - N.A. million Btu / % — COLLECTOR TO DHW LOSS
        - N.A. million Btu / % — COLLECTOR TO SPACE HEATING LOSS
        - N.A. million Btu / % — COLLECTOR TO SPACE COOLING LOSS
      - N.A. million Btu / % — STORAGE TO LOAD LOSS
        - N.A. million Btu / % — STORAGE TO DHW LOSS
        - N.A. million Btu / % — STORAGE TO SPACE HEATING LOSS
        - N.A. million Btu / % — STORAGE TO SPACE COOLING LOSS
  - 0.07 million Btu / 3% — SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data
N.A. - Denotes not applicable data

TABLE E-7. SOLAR ENERGY DISTRIBUTION - MARCH 1979
CHESTER WEST

3.74	100%	million Btu	TOTAL SOLAR ENERGY COLLECTED
*	%	million Btu	SOLAR ENERGY TO LOADS
*	%	million Btu	SOLAR ENERGY TO DHW SUBSYSTEM
0.73	20%	million Btu	SOLAR ENERGY TO SPACE HEATING SUBSYSTEM
N.A.	%	million Btu	SOLAR ENERGY TO SPACE COOLING SUBSYSTEM
*	%	million Btu	SOLAR ENERGY LOSSES
*	%	million Btu	SOLAR ENERGY LOSS FROM STORAGE
*	%	million Btu	SOLAR ENERGY LOSS IN TRANSPORT
*	%	million Btu	COLLECTOR TO STORAGE LOSS
N.A.	%	million Btu	COLLECTOR TO LOAD LOSS
N.A.	%	million Btu	COLLECTOR TO DHW LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE HEATING LOSS
N.A.	%	million Btu	COLLECTOR TO SPACE COOLING LOSS
N.A.	%	million Btu	STORAGE TO LOAD LOSS
N.A.	%	million Btu	STORAGE TO DHW LOSS
N.A.	%	million Btu	STORAGE TO SPACE HEATING LOSS
N.A.	%	million Btu	STORAGE TO SPACE COOLING LOSS
0.24	6%	million Btu	SOLAR ENERGY STORAGE CHANGE

* - Denotes unavailable data
N.A. - Denotes not applicable data